

MEDICAL RESEARCH PROGRAMS, PAST AND FUTURE, FOR DESIGNING SUBMARINE
ATMOSPHERES TO RETARD FIRES

CAPT Douglas R. Knight MC, USN

Approved and Released by:

C. A. Harvey

C. A. HARVEY, CAPT MC USN
Commanding Officer
Naval Submarine Medical Research Laboratory

THE PROBLEM Fires are a constant menace to the survivability of nuclear submarines during peacetime and wartime operations. One strategy for reducing shipboard fire hazards is to lower the concentration of atmospheric oxygen to a safe, minimum level. This level is not known at the present time.

THE FINDINGS The Naval Research Laboratory (NRL) and Naval Submarine Medical Research Laboratory (NSMRL) have been investigating the use of oxygen-lean atmospheres to retard fires aboard submarines. Fire-safety studies at the NRL have indicated the need to operate nuclear submarines with < 19% oxygen in the crew compartment. Trial studies at the NSMRL have indicated that oxygen concentrations can be reduced to 11% for 1-2 hours of exposure. Further work is needed to determine the minimum concentration of oxygen for crew use during heavy work and multiday exposures.

APPLICATION Reductions of the oxygen concentrations in submarine atmospheres may improve ship survivability of fires.

ADMINISTRATIVE INFORMATION

This investigation was conducted as part of NSMRL's reimbursable exploratory research entitled "Crew responses to 19% oxygen in the atmosphere of nuclear submarines." The manuscript was submitted for review on 28 Nov 1986, approved for publication on 7 Feb 1986 and has been designated as NSMRL Memo Report 87-2.

ABSTRACT

One method of improving submarine fire safety is to retard the flammability of combustible materials with atmospheres containing $\leq 19\%$ oxygen. This should only be done if it is known that crews can effectively perform their occupation in the oxygen-lean environment. The purpose of this report is to summarize the history of research in this special topic of submarine medicine. The report is concluded with an outline of work needed to provide submarine commanders the option of using fire-retardant atmospheres aboard patrolling submarines.

ACKNOWLEDGEMENT. The author wishes to thank Dr. Homer Carhart, and his colleagues at the Naval Research Laboratory, for initiating the development of this line of research at the Naval Submarine Medical Research Laboratory.

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THE NEED FOR BIOMEDICAL RESEARCH

Question. Sixty one fires caused one million dollars worth of damage to submarines over a time period of four years (Jan 75-Dec 79). Half the fires occurred at sea and practically all were started by the malfunctioning of electrical equipment. There were 13 injuries and a total loss of 292 operating days (1). In a subsequent period of four years, 104 submarine fires were reported to cost the Navy in excess of six million dollars. The burning materials included hull insulation, electrical circuit breakers, oxygen generators, galley ranges, and emergency propulsion motors (2). Laboratory simulations of submarine hull insulation fires quickly raised compartment temperatures to fatal levels (3), indicating that a conflagration could easily destroy a ship in a short period of time. For these reasons, the Naval Research Laboratory (NRL) suggested reducing material fire ignition, fire spread, and flammability characteristics by lowering the oxygen concentrations in submarines (4).

In 1979, members of the Naval Sea System Command's COMMITTEE ON SUBMARINE FIRE PREVENTION AND CONTROL reviewed the strategy of retarding fires by lowering the concentrations of oxygen in the crew's space. Medical representatives expressed concern about side effects such as headaches, shortness of breath, and constriction of the peripheral vision (5). Therefore, the Naval Sea Systems Command sought advice from the Naval Bureau of Medicine and Surgery (appendix a). The Medical Department did not recommend changing the range of oxygen levels already specified for submarine crews, since little was known about the long-term effects of exposing crews to reduced levels of oxygen in atmospheres containing trace contaminants.

In 1983, the use of low oxygen concentrations was readdressed in a Navy sponsored workshop on submarine atmospheres (11). Discussions at the Workshop led to a review of the literature and publication of a position paper (6). That paper (6) supported the strategy of fire suppression and emphasized a need for conducting research on the biomedical effects of long exposures to oxygen levels ≤ 140 torr in an atmosphere containing trace contaminants.

Crews of Naval submarines are authorized to operate with 17.5-19% oxygen for an unspecified period of time. Excursions below 17.5% oxygen are unauthorized because regulations limit the minimum partial pressure of oxygen (P_{O_2}) to 140 torr and the maximum barometric pressure (P_B) to 800 torr. [percentage oxygen = $100(P_{O_2}/P_B)$]. Submarine crews may be able to operate with oxygen pressures below 140 torr, since U.S. Air Force flight crews perform complex military tasks while breathing oxygen

partial pressures ≤ 130 torr. The question is, "How low can the oxygen concentration be reduced without impairing the health and performance of submarine crews?"

Hypothesis. Medical scientists generally acknowledge that oxygen's partial pressure, not its concentration, determines the level of human performance. Residents at Denver, U.S.A.F. flight crews, and some submarine crews share the common feature of working in atmospheres with P_{O_2} 's ≤ 130 torr for periods of time ranging from a few hours to lifetime exposures. Although the submarine exposures to low P_{O_2} 's were not a matter of routine, it is worth emphasizing that the crews operated their ships successfully (6). Laboratory studies have defined the human tolerance for brief exposures to oxygen-deficient atmospheres. Visual function, which seems to be the biological function most sensitive to hypoxia, was not impaired until $P_{O_2} \leq 130$ torr. At P_{O_2} 130 torr, the maximal performance of exercise was only slightly impaired (6).

If submarine crews work effectively at P_{O_2} 130 torr, 13% oxygen could provide adequate life support at barometric pressures ≥ 1000 torr. Some engineering and operational limitations may have to be resolved in order to raise the atmospheric pressure above 800 torr, but the crew would tolerate short-term exposures. Long exposures to hyperbaric nitrogen introduce the risk of decompression sickness after workers return to sea-level pressure. For example, decompression sickness could develop after 48-hour exposures to partial pressures of nitrogen (P_{N_2}) ≥ 1064 torr. Therefore, the minimum concentration of oxygen in the crew's atmosphere is significantly influenced by the necessity of avoiding HYPOXIA and DECOMPRESSION SICKNESS. This indicates that atmospheric pressure should not exceed 1194 torr when $P_{N_2} \leq 1064$ torr and $P_{O_2} \geq 130$ torr. At minimum P_{O_2} (130 torr) and maximum P_B (1194 torr), submarine crews could effectively operate with a very low concentration of oxygen (11%).

THE INITIAL RESEARCH AT THE NAVAL SUBMARINE MEDICAL RESEARCH LABORATORY

Although reduction of the oxygen concentration to 19% is theoretically sound, additional exposures to 0.7-1.0% carbon dioxide and other trace contaminants should be evaluated (2,5,7). Two research projects were designed to achieve the following objectives (6,8):

- first, determine the long-term effects of operating with 19% oxygen, and transient reductions to 17%, in atmospheres contaminated by 0.7-1.0% carbon dioxide and low concentrations of organic molecules.
- second, define the absolute minimum concentration of oxygen for use aboard nuclear submarines.

6.1 PROGRAM. Preliminary experiments were performed at the Naval Submarine Medical Research Laboratory (NSMRL) in SEP-OCT 1985. The

objectives were to test visual function in 11-17% oxygen and evaluate the effect of 3% carbon dioxide on the visual function of oxygen-deficient subjects. Seven healthy men were exposed to each of the following conditions:

	<u>%O₂</u>	<u>P_B, torr</u>	<u>P_{O₂}, torr</u>	<u>P_{CO₂}, torr</u>
1.	20.9	760	159	0
2.	16.8	760	128	5
3.	13.4	970	130	7
4.	13.0	760	99	0
5.	20.9	760	159	24
6.	13.0	760	99	24
7.	11.0	760	84	0

Compared to measurements in 21% oxygen, 11-17% oxygen did not change the threshold intensities of light for nighttime vision and contrast sensitivity. The subjects tended to feel dizzy when breathing 11-13% oxygen at P_B = 760 torr, but none became ill during the 2-3 hour

1. In fact, many nuclear submarines routinely operate with 19% oxygen in the floodable volume (12).

exposures. The addition of 3% carbon dioxide (P_{CO₂} 24 torr) to 20.9% and 13% oxygen did not change visual function. These results indicated that brief exposures to 11-17% oxygen did not degrade visual function when oxygen's partial pressure was 130 torr and the atmosphere was contaminated with trace levels of carbon dioxide.

6.3 PROGRAM. On 1 Nov 85, the NSMRL was tasked by the Naval Sea Systems Command to study the effects of reduced oxygen concentration on submariners. A draft-proposal was promptly submitted to the CO, NSMRL, for approval of the experimental plans and use of volunteer, human subjects. A committee of two scientists and one submarine commander visited the NSMRL on January 28, 1986, to review the research plans for FY 86-87 (9).

A review of atmosphere logs showed that Atlantic Fleet submarines occasionally operate outside of the specified OXYGEN ZONE. The minimum P_{O₂} was 127 torr (normally \geq 140 torr) and the maximum P_B was 862 torr (normally \leq 800 torr). This strongly suggests that the oxygen zone can be modified to P_{O₂} 130 torr, P_B 850 torr without modifying the engineering plants of today's submarines.

6.3 funds for research were discontinued in October, 1986, due to a severe cut in the program budget.

FUTURE RESEARCH AT THE NAVAL SUBMARINE MEDICAL RESEARCH LABORATORY

The support for future medical research should be based on a core program that is supplemented by reimbursable funding from the Naval Sea Systems Command. The Office of Naval Technology is the most appropriate sponsor for the core program, since much exploratory research (6.2 program) still needs to be done. Reimbursable funding (6.3-6.5 programs) is needed to develop equipment, test procedures, and conduct sea-trials.

6.1-6.2 PROGRAM

PUBLICATIONS OF FUNDAMENTAL DATA

PROBLEMS

- According to enclosure 1 of BUMED letter (BUMED-3C2:RLS:sdh, 6420, 21 January 1980), "the problems associated with long-term exposure to this oxygen level (19%), in conjunction with an increased inspired P_{CO_2} (F_{CO_2}) of 0.7-1.0% and trace contaminants in the atmosphere, are unknown at this time."
- NSMRL's trial studies have not demonstrated the trade-off between effects of P_{O_2} and F_{O_2} on performance.

COLLECT DATA

- Use hyperbaric exposures to demonstrate that human performance is a function of P_{O_2} , not % oxygen. [isopleths of acceptable and unacceptable P_{O_2} s from ordered pairs of (P_B, F_{O_2})]
- Show that the flammability of hair/biological specimens depends on % oxygen.
- Study the effect of hypoxia on the metabolism of trace contaminants absorbed from submarine air.
- Search the literature for data on human performance during acute withdrawal from cigarette smoking.

DEVELOP

- A computer program for prediction of survival time during breathe-down of oxygen from the floodable volume.

6.2-6.3 PROGRAM

A REDESIGNED O₂ ZONE: 130 TORR O₂/800 TORR $P_B = 16.3\% O_2$

PROBLEM

- The NAVSEA Submarine Fire Protection Committee wants to reduce the lower limit of P_{O_2} in the submarine oxygen zone to 130 torr. This would permit excursions of oxygen concentration to 17% when operating with 19% oxygen in the floodable volume.

LABORATORY STUDIES

- Document the effects of 3-day exposures to P_{O_2} 's 100, 130, and 160 torr.
- Document the effect of a partial vacuum (P_B 608 torr) on human tolerance of 16% oxygen.
- Determine the minimum P_{O_2} which permits effective human performance.

FIELD STUDIES

- Compare the effects on human performance of patrolling with P_{O_2} 130 torr in the submarine atmosphere to the effects of working in 150-160 torr oxygen.

RECOMMENDATIONS

- Draft a change to the atmosphere control manual.

A REDESIGNED O2 ZONE: 130 TORR O2/850 TORR $P_B = 15.3\% O_2$

PROBLEM

- Atmosphere Logs have shown that the barometric pressure occasionally rises to a range of 800-862 torr in patrolling submarines.

COLLECT DATA

- Prepare an up-to-date scatterplot of hourly (P_B, P_{O_2})'s from submarine atmosphere logs.
- Review data on decompressions from hyperbaric nitrogen.

ANALYZE DATA

- Determine violations of the current oxygen zone from the scatterplot of (P_B, P_{O_2})'s.
- Predict the maximum P_B safe for use with negligible risk of decompression sickness.

LABORATORY STUDIES

- Through the use of models and experiments, determine the maximum P_{N_2} permitting safe, no-stop decompression of saturated men.

FIELD STUDIES

- Test the performance of engineering equipment when barometric pressure is raised to ≥ 850 torr during fast-cruise.
- Test the performance of machinery and men when barometric pressure is raised to 850 torr at sea.

A REDESIGNED O2 ZONE: 130 TORR O2/1194 TORR $P_B = 11\% O_2$

LABORATORY STUDIES

- Define, by experimentation, the limiting P_B and P_{O_2} for safe sea-trials.

SEA-TRIALS

- Dockside studies.
- Trials at sea.

6.3-6.5 PROGRAM

A COMPUTER PROGRAM FOR MAINTENANCE OF THE O₂ ZONE

PROBLEM

- Atmosphere Logs have shown that the barometric pressure and P_{O_2} exceed currently accepted limits when the oxygen zone is manually maintained by the crew.

PROCURE OR WRITE ALGORITHMS

- Determine the progress-to-date made by NAVSEA, NRL, and SUBRON-12 with respect to computer control of the atmosphere.
- Control the maintenance of a fire-retardant oxygen zone within tight limits for P_B and P_{O_2} .
- Control the recovery from sudden changes of P_B and P_{O_2} .
- Control the P_B and P_{O_2} for minimal risk of decompression sickness.

ADAPT THE ALGORITHM FOR USE AT SEA

- Prepare a prototype system, using resources available at SUBSCHL, the Electric Boat Company, SUBRON 12, and NAVSEA.
- Debug the program

SEA-TRIALS

- Dockside trials.
- Trials at sea.

POINT PAPER

PROBLEM

- The engineering costs and benefits of using an oxygen-lean atmosphere to improve fire-safety aboard submarines have not been determined.

THEORETICAL ENGINEERING CONCERNS

- Diminished function of equipment in low-level oxygen.
- Damage at hyperbaric pressures.
- Space and weight limitations
- Incipient fires and monofuel combustion

THEORETICAL MEDICAL CONCERNS

- Hypoxia
- Decompression sickness
- Withdrawal from smoking
- Barotrauma
- Anaerobic metabolism of atmospheric contaminants
- Asphyxiants in the atmospheric contaminants
- Reduced survival time in a sunken submarine

COLLECT DATA

- Interview engineers and operators.
- Review data on flammability of materials in oxygen-lean atmospheres.

ANALYZE DATA

- Define the pressure- and oxygen sensitive equipment aboard submarines.
- Outline the improvements in fire-safety with graded reductions of % oxygen.

REPORT DATA

- Losses of equipment/human function with graded reductions of P_{O_2} .
- Losses of equipment/human function with graded increments of P_B .

ADMINISTRATIVE POLICY

If the experimental results of laboratory studies and field tests show that crews can effectively operate in fire-retardant, oxygen-lean atmospheres, THE NAVAL SUBMARINE MEDICAL RESEARCH LABORATORY WILL RECOMMEND CHANGES OF POLICY REGARDING THE CONTROL OF SUBMARINE ATMOSPHERES. THE APPROPRIATE AUTHORITY FOR REVIEWING AND ADJUDICATING THE EXPERIMENTAL RESULTS OF THIS RESEARCH PROJECT IS THE NAVAL MEDICAL COMMAND.

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appendix a. EXCERPTS FROM NAVAL CORRESPONDENCE

REQUEST FOR ADVICE

Serial: 92D/Ser 181
NOV 27 1979
From: Commander, Naval Sea Systems Command
To: Chief, Bureau of Medicine and Surgery
Subj: Reduced oxygen levels onboard operating submarines

1., "the Naval Research Laboratory (NRL) has proposed a study to examine the reduction of material fire ignition, fire spread and flammability characteristics as a result of reducing oxygen levels within the submarine to a target of 19 percent."
3. "THE CURRENT PRACTICE OF WEEKLY VENTILATION OF THE SUBMARINE WILL CAUSE OXYGEN LEVELS OF 20.5 - 21.0 PERCENT. FOLLOWING THIS, IT CAN BE EXPECTED THAT A 19 PERCENT OXYGEN LEVEL WILL TAKE 1 - 2 DAYS TO BE REACHED, WITH NORMAL SWINGS THEREAFTER OF + 0.5 PERCENT. HOWEVER, OCCASIONAL EXCURSIONS DURING OPERATIONS CAN REDUCE OXYGEN LEVELS TO 17 PERCENT."
4. "It is requested that BUMED comment on the permissibility and physiological effect of maintaining oxygen levels as defined in paragraph 3 above."

ADVISORY LETTER

Serial: BUMED-3C2:RLS:sdh
6420
21 January 1980
From: Chief, Bureau of Medicine and Surgery
To: Commander, Naval Sea Systems Command (NAVSEA-5314)
Subj: Reduced oxygen levels onboard operating submarines...
Ref: (b) Nuclear Powered Submarine Atmosphere Control
Manual S9510-AB-ATM-010/(C) SubAtmCont
Encl: (1) NMRDC memo 41/3910 of 19 December 1979

3. "UNTIL IT IS POSSIBLE TO STATE WITH A GREATER DEGREE OF CONFIDENCE THAT LONG-TERM MAINTENANCE OF REDUCED OXYGEN LEVELS WOULD HAVE NO ADVERSE PHYSIOLOGICAL OR BEHAVIORAL EFFECT, the Chief, Bureau of Medicine and Surgery considers it advisable to USE ONLY THE RANGE OF OXYGEN LEVELS SPECIFIED IN REFERENCE (B)."

Enclosure (1).

1., "the problems associated with long-term exposure to this oxygen level (19%), in conjunction with an increased inspired P_{CO_2} of 0.7-1.0% and trace contaminants in the atmosphere, are unknown at this time."

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
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11. CONTROLLING OFFICE NAME AND ADDRESS Naval Med. Rsch and Dev. Command Naval Medical Command, NCR Bethesda, MD 20814 - 5044		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) One method of improving submarine fire safety is to retard the flammability of combustible materials with atmospheres containing \leq 19% oxygen. This should only be done if it is known that crews can effectively perform their occupation in the oxygen-lean environment. The purpose of this report is to summarize the history of research in this special topic of submarine medicine. The report is concluded with an outline of work needed to provide submarine commanders the option of using fire-retardant atmospheres aboard patrolling		

